Quarkonium Production
References

- Geoff Bodwin

  – Quarkonium Production and Decay:

  NRQCD Confronts Experiment

  Program on Effective Field theories

  in Particle and Nuclear Physics

  KITPC, August 2009

- Pierre Artoisenet

  Status of Theory Calculations & LHC Predictions

  Workshop on Quarkonium Production

  CERN, February 2010

  –

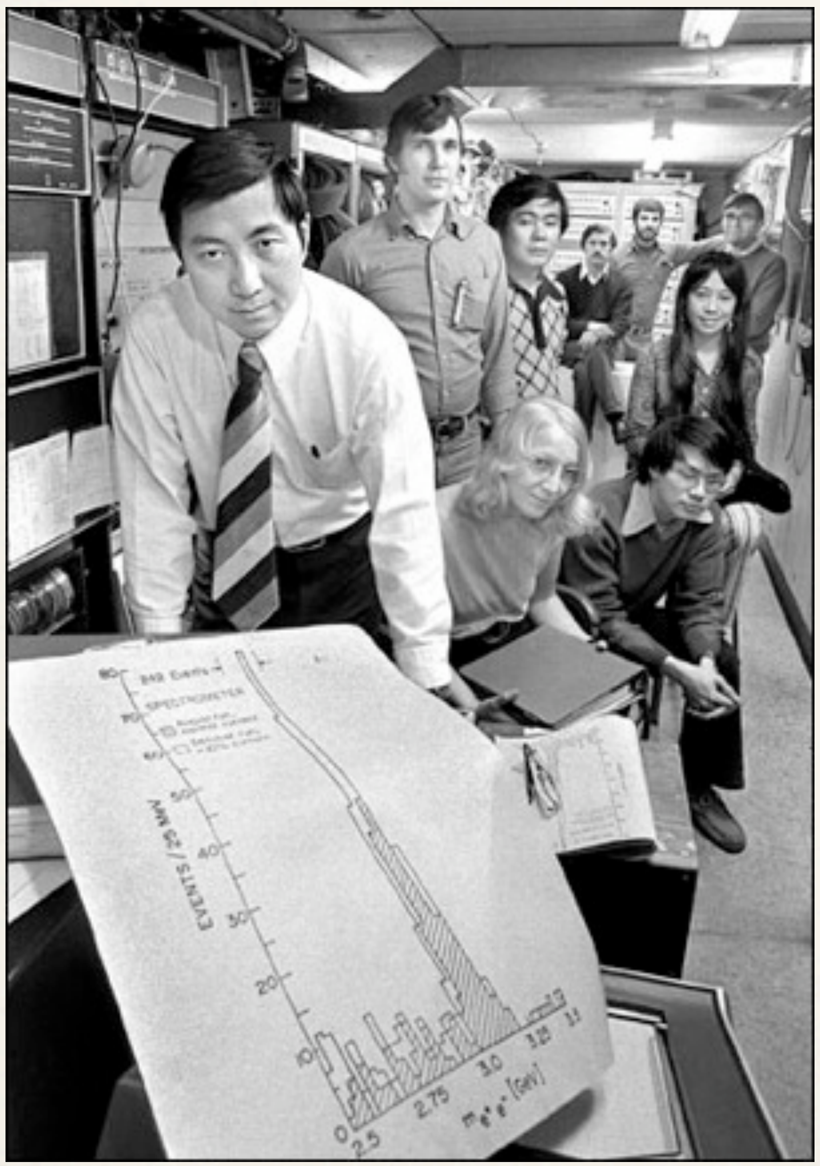
Stumbling towards a Theory of Quarkonium Production

Eric Braaten
The Ohio State University

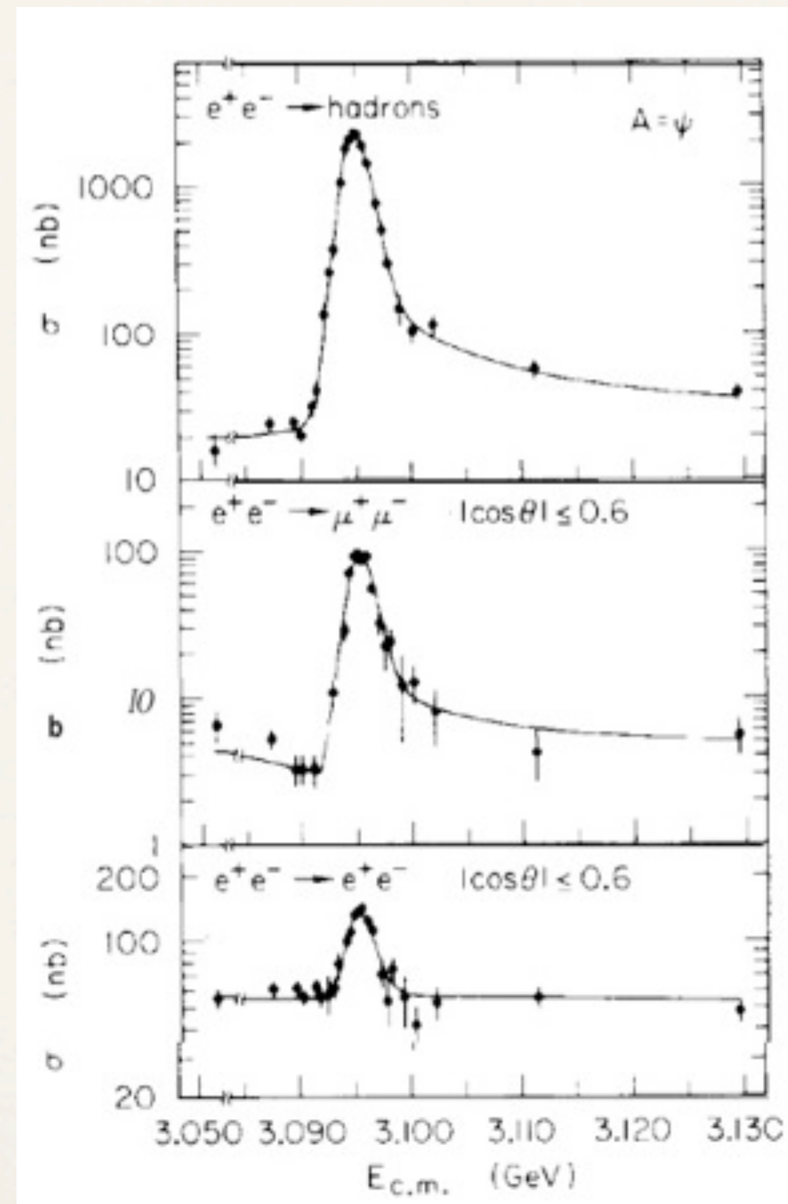
Fermilab, May 21, 2010

Discovery of Charmonium
November 1974

p on Be target at Brookhaven



e^+e^- annihilation at SLAC

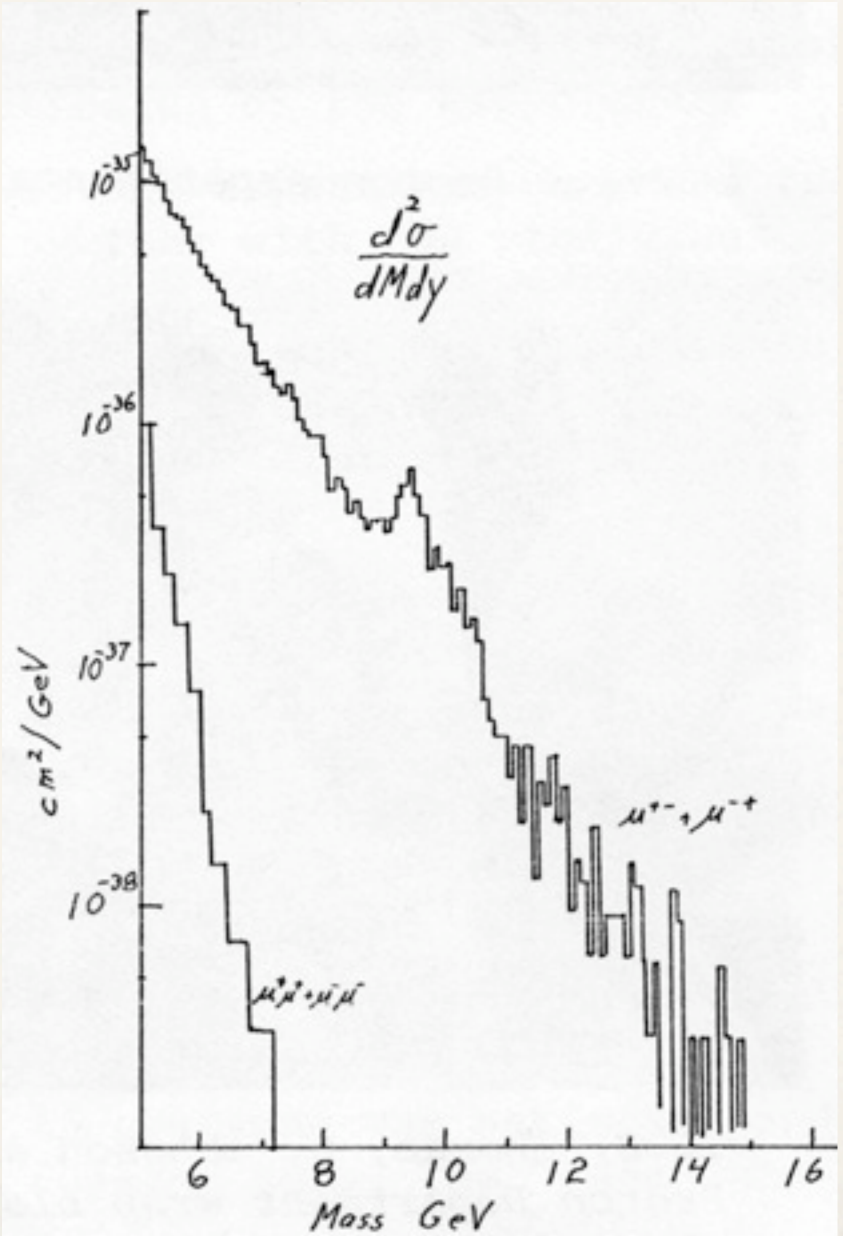


$p\,N \;\rightarrow\; J/\psi + X,\;\; J/\psi \;\rightarrow\; e^+e^-$

$e^+e^- \;\rightarrow\; J/\psi,\;\; J/\psi \;\rightarrow\;$ hadrons

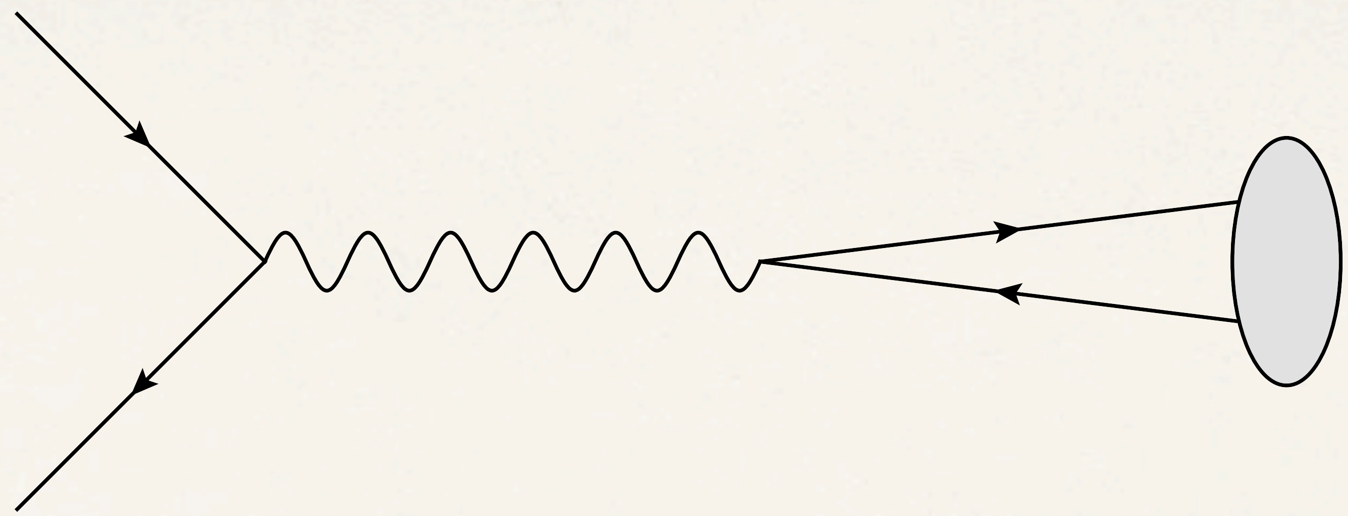
Discovery of Bottomonium
August 1977

p on Be target at Fermilab



$$p\,N \rightarrow \Upsilon + X,\ \Upsilon \rightarrow \mu^+\mu^-$$

e^+e^- annihilation into J/ψ



- $c\ \bar{c}$ created by virtual photon

- rate determined by one constant f_ψ

$$\langle J/\psi|\bar{c}\gamma^\mu c|0\rangle = f_\psi\ \epsilon^\mu_\psi$$

- estimate using potential models: $f_\psi \propto R(0)$

- can be calculated using lattice QCD
  NRQCD, HPQCD, ...

Production of Charmonium using Hadrons

- How is the $c\,\bar{c}$ pair created?
  What are the relevant parton processes?
  Can they be calculated using perturbative QCD?

- How does the $c\,\bar{c}$ pair bind to form charmonium?
  Can effects of binding be reduced to a few constants?
  Can they be calculated using lattice QCD?

- Possible answers: Color-singlet model (1976?)
  Color evaporation model (1977)
  NRQCD factorization (1995)

Color-singlet Model

Ellis, Einhorn, Quigg 1976; Carlson and Suaya 1976; Kuhn 1980; Degrand, Toussaint 1980; Kuhn, Nussinov, Ruckl 1980; Wise 1980; Chang 1980; Baier, Ruckl 1981; Berger, Jones 1981

- $c\,\bar{c}$ is created by parton collisions
  with negligible relative momentum

- $c\,\bar{c}$ can bind into charmonium only if it is created
  in same color/angular momentum as in charmonium
  $\underline{1}\ {}^3S_1$ for J/ψ
  $\underline{1}\ {}^3P_J$ for χ_{cJ}

- probability that $c\,\bar{c}$ binds into charmonium
  is determined by wavefunction near origin
  $\propto R(0)$ for $J/\psi,\ \eta_c$
  $\propto R'(0)$ for $\chi_{cJ},\ h_c$

  one constant for each multiplet
  can be determined from annihilation decays: $J/\psi \to e^+\,e^-$
  $\chi_{c0} \to \gamma\,\gamma$

Color Evaporation Model

Fritzsch 1977; Halzen 1977

- $c\,\bar{c}$ pair is created by parton collisions
  with invariant mass below $D\,\bar{D}$ threshold
  (between $2m_c$ and $2m_D$)

- $c\,\bar{c}$ pair can bind into charmonium regardless
  of its color / angular momentum state

- probability that $c\,\bar{c}$ binds to form charmonium H
  is universal constant f_H for each multiplet

Color-singlet Model vs Color Evaporation Model

- Applicability

  CSM: exclusive and inclusive production
  definite predictions for polarization

  CEM: only sufficiently inclusive production
  no polarization

- Predictive power

  CSM: one constant for each multiplet
  determined by annihilation decays

  CEM: one constant for each multiplet
  adjustable parameters

Color-singlet Model vs Color Evaporation Model

- consistency

  CSM: infrared divergences for P-waves

  CEM: no infrared divergences

$\chi_{cJ} \to q\,q\,g$

$b \to \chi_{cJ} + s + g$

- perturbative corrections

  CSM: separate NLO calculation for each process

  CEM: can use NLO calculation for inclusive $Q\bar{Q}$

  Nason, Dawson, Ellis 1988

- Dominant theoretical prejudice in early 1990's

  CSM: can probably be extended to a theory based on QCD

  CEM: purely phenomenological model

Color-singlet Model vs Color Evaporation Model

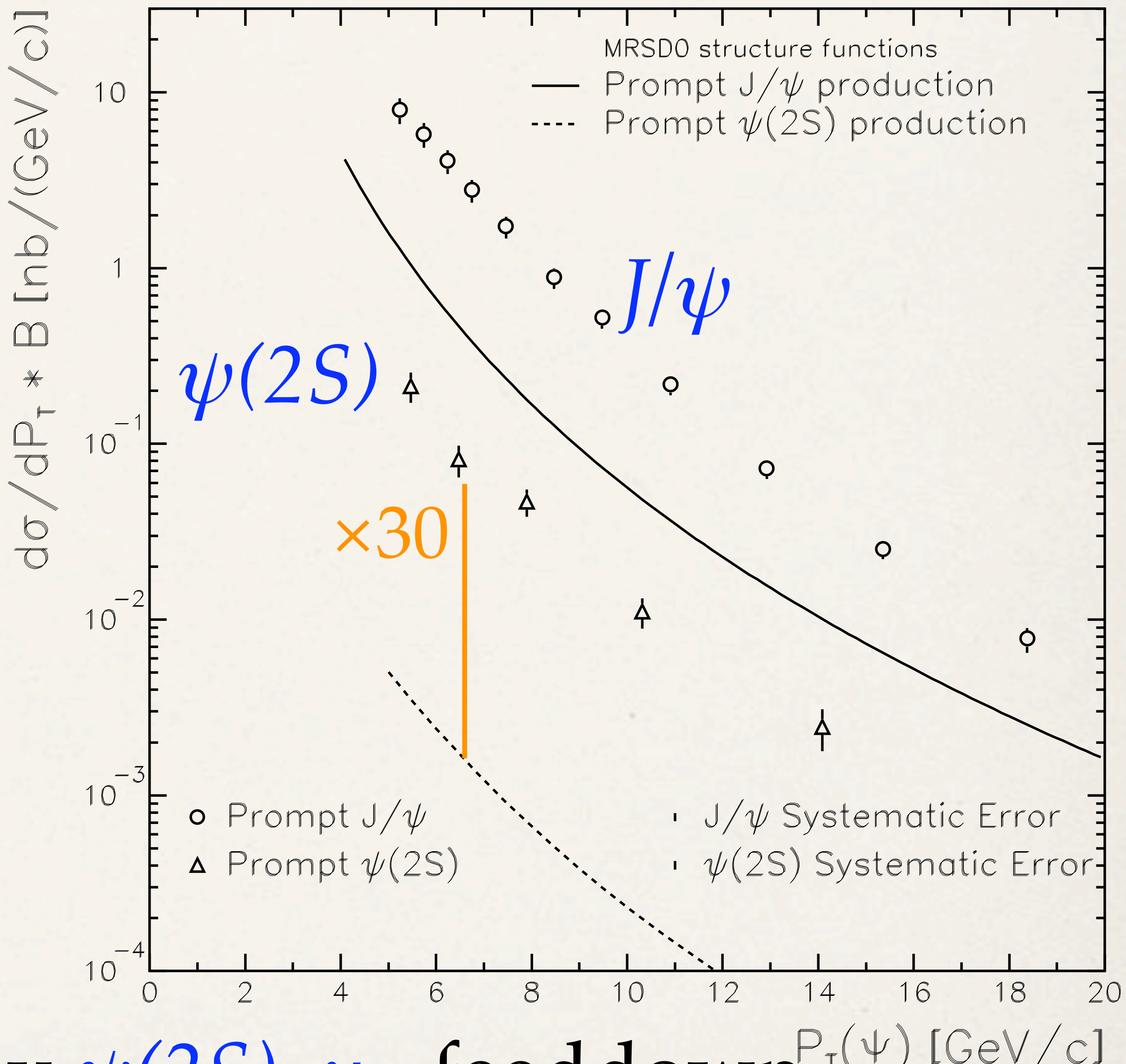
Experimental status in early 1990's

- Fixed target experiments (pN, πN, γN)
  - feeddown to J/ψ from $\psi(2S)$, χ_{cJ} decays
  - contributions from small p_T $\Rightarrow$ nonperturbative?
  - large experimental errors
  - roughly compatible with CSM or CEM
- $p\,\bar{p}$ collisions at the Tevatron
  - feeddown to J/ψ from $\psi(2S)$, χ_{cJ} decays
  - feeddown from B decays
  - $p_T > 5$ GeV $\Rightarrow$ perturbative?
  - production rates much larger than predicted by CSM?

Demise of Color-singlet Model

CDF collaboration 1997

- use vertex detector to remove B feeddown



- prompt J/ψ: complicated by $\psi(2S)$, χ_{cJ} feeddown
- prompt $\psi(2S)$: 30 times larger than CSM prediction (in retrospect, compatible with CEM)

Nonrelativistic QCD

Caswell and Lepage 1986

- effective field theory for $Q\bar{Q}$ sector of QCD
  at energies << m_Q from $Q\bar{Q}$ threshold

- in quarkonium, small velocity v is generated dynamically
  by balance between potential energy
  and kinetic energy
  charmonium: $v^2 \approx 1/3$
  bottomonium: $v^2 \approx 1/10$

- nonperturbative effects
  can be organized according to their scaling with v

Nonrelativistic QCD (cont.)

Multipole expansion

- E1 transitions: $\Delta L = 1, \Delta S = 0$ amplitude ~ v
- M1 transitions: $\Delta L = 0, \Delta S = 1$ amplitude ~ v^2

Fock state expansion for quarkonium
can be organized in powers of v

$$|J/\psi\rangle = \mathcal{O}(1)\ |c\bar{c}(\underline{1}\ {}^3S_1)\rangle + \mathcal{O}(v)\ |c\bar{c}(\underline{8}\ {}^3P_J) + g\rangle + \mathcal{O}(v^2)$$

Lattice NRQCD Lepage et al. 1992

calculate properties of quarkonium nonperturbatively

NRQCD, HPQCD, ...

NRQCD Factorization

Bodwin, Braaten and Lepage 1995

- apply NRQCD to
  annihilation decays/inclusive production of quarkonium

- motivation:
  infrared divergences for P-waves in CSM

  decays $\chi_{cJ} \to q\,\bar{q}\,g$

  production $b \to \chi_{cJ} + s + g$

- use effective field theory NRQCD
  to separate hard momentum scales (m_Q and larger)
  from soft momentum scales ($m_Q v$ and smaller)

- annihilation/creation of $Q\bar{Q}$ pair: hard

- evolution/formation of quarkonium: soft

NRQCD Factorization (cont.)

Annihilation decay rate of charmonium H

$$\Gamma[H] = \sum_n \hat{\Gamma}[c\bar{c}(n)]\ \langle H|\mathcal{O}_n|H\rangle$$

- sum over color/angular momentum channels

  $\underline{1}$ or $\underline{8}$ $\quad {}^1S_0$, ${}^3S_1$, ${}^1P_1$, ${}^3P_0$, ${}^3P_1$, ${}^3P_2$, ...

- hard factors: annihilation rate for $c\bar{c}$ into partons

  expand in powers of $\alpha_s(m_c)$

- soft factors: NRQCD matrix elements

  scale as powers of v

- <u>rigorous</u> factorization formula

  double expansion in $\alpha_s(m_c)$ and v

NRQCD Factorization (cont.)

Annihilation decay rate of charmonium *H*

$$\Gamma[H] = \sum_n \hat{\Gamma}[c\bar{c}(n)]\ \langle H|\mathcal{O}_n|H\rangle$$

- velocity scaling of NRQCD matrix elements

$$J/\psi: \quad \boxed{\langle \underline{1}\ {}^3S_1\rangle} \sim v^3$$

$$\langle \underline{8}\ {}^3P_J\rangle, \langle \underline{8}\ {}^1S_0\rangle, \langle \underline{8}\ {}^3S_1\rangle \sim v^7$$

CSM

$$\chi_{cJ}: \quad \boxed{\langle \underline{1}\ {}^3P_J\rangle}, \langle \underline{8}\ {}^3S_1\rangle \sim v^5$$

- solves infrared divergence problem for P-waves

- spin symmetry relates J/ψ, η_c

χ_{c0}, χ_{c1}, χ_{c2}, h_c

NRQCD Factorization (cont.)

Inclusive production of charmonium H

$$d\sigma[H] = \sum_n d\hat{\sigma}[c\bar{c}(n)]\ \langle \mathcal{O}_n^H \rangle$$

- sum over color / angular momentum channels

  $\underline{1}$ or $\underline{8}$ $\quad {}^1S_0,\ {}^3S_1,\ {}^1P_1,\ {}^3P_0,\ {}^3P_1,\ {}^3P_2, \ldots$

- hard factors: parton cross sections for creating $c\bar{c}$

  expand in powers of $\alpha_s(m_c)$

- soft factors: NRQCD matrix elements

  scale as powers of v

- conjectured factorization formula

  motivated by perturbative QCD factorization theorems

NRQCD Factorization (cont.)

Inclusive production of charmonium H

$$d\sigma[H] = \sum_n d\hat{\sigma}[c\bar{c}(n)]\ \langle \mathcal{O}_n^H \rangle$$

- velocity scaling of NRQCD matrix elements

CSM

$$J/\psi: \quad \boxed{\langle \underline{1}\ {}^3S_1 \rangle} \sim v^3$$

$$\chi_{cJ}: \quad \boxed{\langle \underline{1}\ {}^3P_J \rangle},\ \langle \underline{8}\ {}^3S_1 \rangle \sim v^5$$

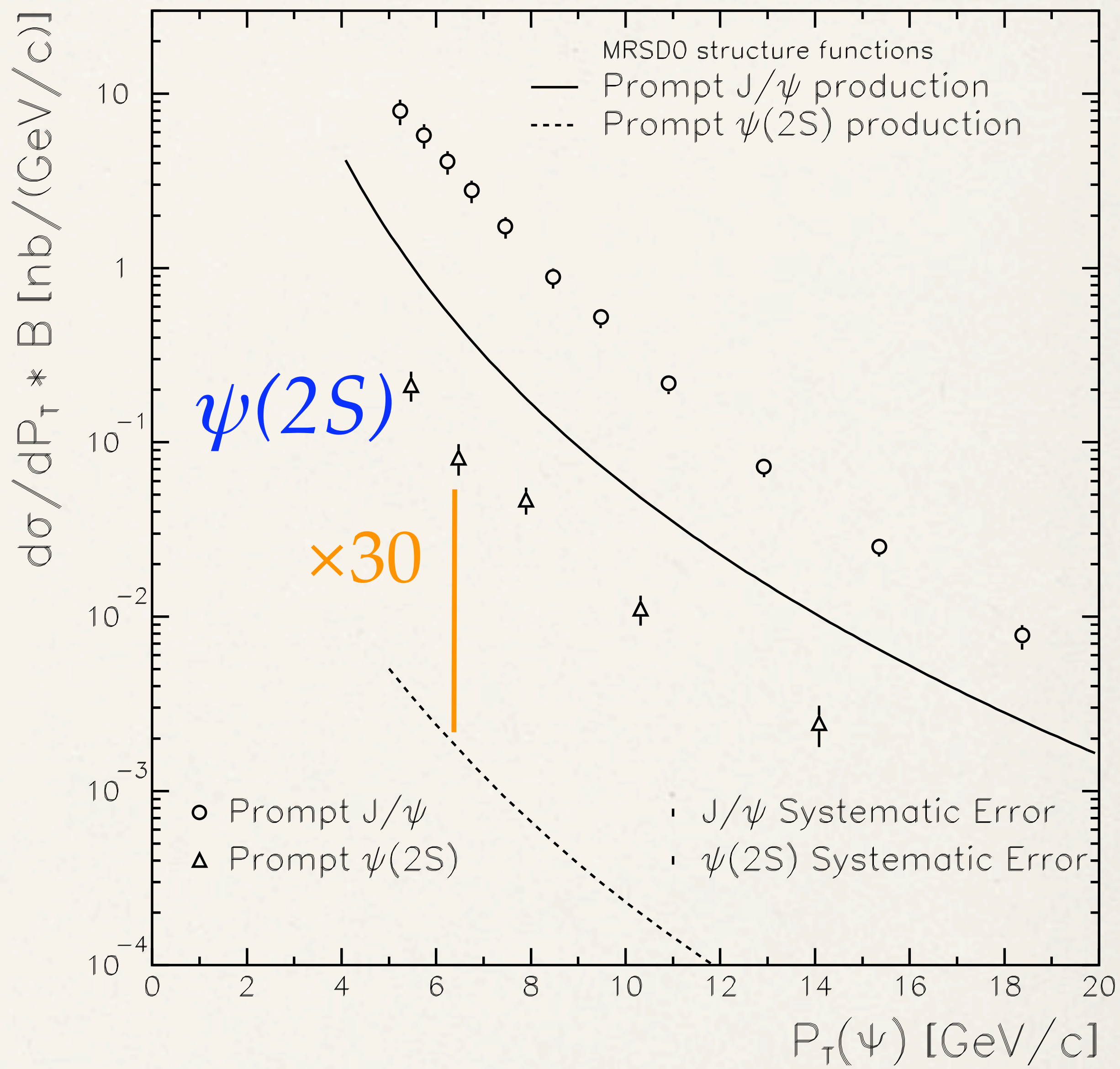
- solves infrared divergence problem for P-waves

- vacuum saturation approximation
  relates CSM matrix elements for production and decay

$\psi(2S)$ Surplus at the Tevatron

CDF collaboration

- prompt $\psi(2S)$ is 30 times larger than CSM prediction



feeddown from P-wave or D-wave charmonium?

charmonium hybrids?

Color evaporation model?

$\psi(2S)$ Surplus at the Tevatron

- NRQCD Factorization predicts
both color-singlet and color-octet production mechanisms

$$\psi(2S): \qquad \langle \underline{1}\ {}^3S_1 \rangle \sim v^3$$
$$\langle \underline{8}\ {}^3P_J \rangle, \langle \underline{8}\ {}^1S_0 \rangle, \langle \underline{8}\ {}^3S_1 \rangle \sim v^7$$

- at large p_T,
CSM term $\langle \underline{1}\ {}^3S_1 \rangle$ is suppressed by α_s^2
color-octet terms $\langle \underline{8}\ {}^1S_0 \rangle$, $\langle \underline{8}\ {}^3P_J \rangle$ are suppressed by $\alpha_s\, v^4$
color-octet term $\langle \underline{8}\ {}^3S_1 \rangle$ is suppressed only by v^4

- proposed solution to $\psi(2S)$ surplus:
prompt $\psi(2S)$ at large p_T at the Tevatron
is dominated by $\langle \underline{8}\ {}^3S_1 \rangle$ term (color-octet mechanism)

Braaten and Fleming 1995

NRQCD Factorization Model

Inclusive production of charmonium H

$$d\sigma[H] = \sum_n d\hat{\sigma}[c\bar{c}(n)] \, \langle \mathcal{O}_n^H \rangle$$

- for S-waves, truncate after order v^7

$$J/\psi : \qquad \langle \underline{1} \ {}^3S_1 \rangle \sim v^3$$
$$\langle \underline{8} \ {}^3P_J \rangle, \langle \underline{8} \ {}^1S_0 \rangle, \langle \underline{8} \ {}^3S_1 \rangle \sim v^7$$

$\Rightarrow$ 4 universal constants for J/ψ, η_c
(1 determined by $J/\psi \to e^+e^-$)

- for P-waves, truncate after order v^5

$$\chi_{cJ} : \qquad \langle \underline{1} \ {}^3P_J \rangle, \langle \underline{8} \ {}^3S_1 \rangle \sim v^5$$

$\Rightarrow$ 2 universal constants for χ_{c0}, χ_{c1}, χ_{c2}, h_c
(1 determined by $\chi_{c0} \to \gamma\gamma$)

NRQCD Factorization Model

Inclusive production of charmonium H

$$d\sigma[H] = \sum_n d\hat{\sigma}[c\bar{c}(n)] \, \langle \mathcal{O}_n^H \rangle$$

- for S-waves, truncate after order v^7

$$J/\psi: \quad \boxed{\langle \underline{1}\ {}^3S_1 \rangle} \sim v^3$$

$$\langle \underline{8}\ {}^3P_J \rangle, \boxed{\langle \underline{8}\ {}^1S_0 \rangle, \langle \underline{8}\ {}^3S_1 \rangle} \sim v^7$$

CSM

$\Rightarrow$ 4 universal constants for J/ψ, η_c

(1 determined by $J/\psi \rightarrow e^+e^-$)

CEM

- for P-waves, truncate after order v^5

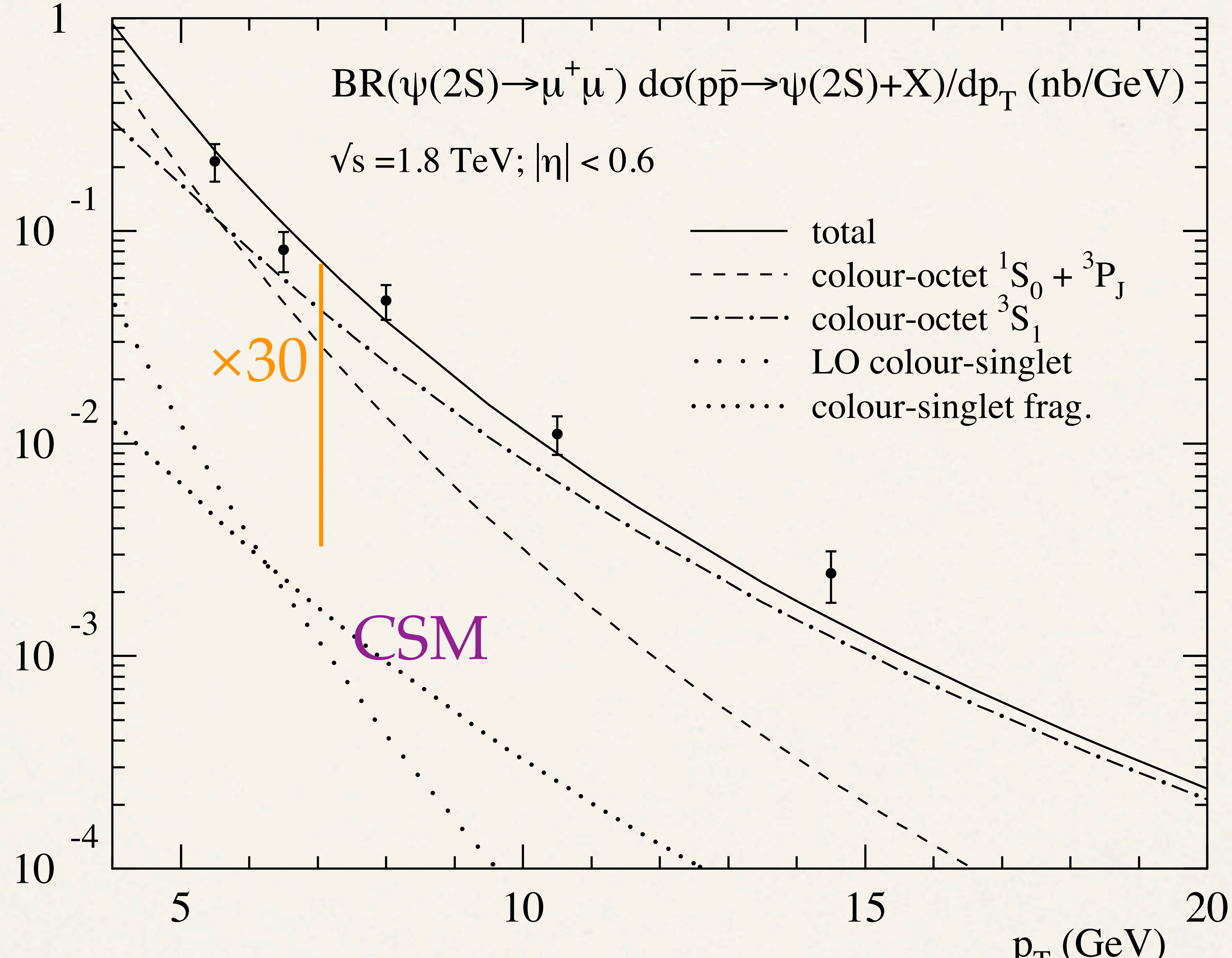
$$\chi_{cJ}: \quad \boxed{\langle \underline{1}\ {}^3P_J \rangle}, \boxed{\langle \underline{8}\ {}^3S_1 \rangle} \sim v^5$$

$\Rightarrow$ 2 universal constants for χ_{c0}, χ_{c1}, χ_{c2}, h_c

(1 determined by $\chi_{c2} \rightarrow \gamma\gamma$)

NRQCD Factorization Model

CDF data on prompt $\psi(2S)$



fit $\langle \underline{8}\ {}^3S_1 \rangle$ and $\langle \underline{8}\ {}^1S_0 \rangle$ (or $\langle \underline{8}\ {}^3P_J \rangle$) Kramer 2001

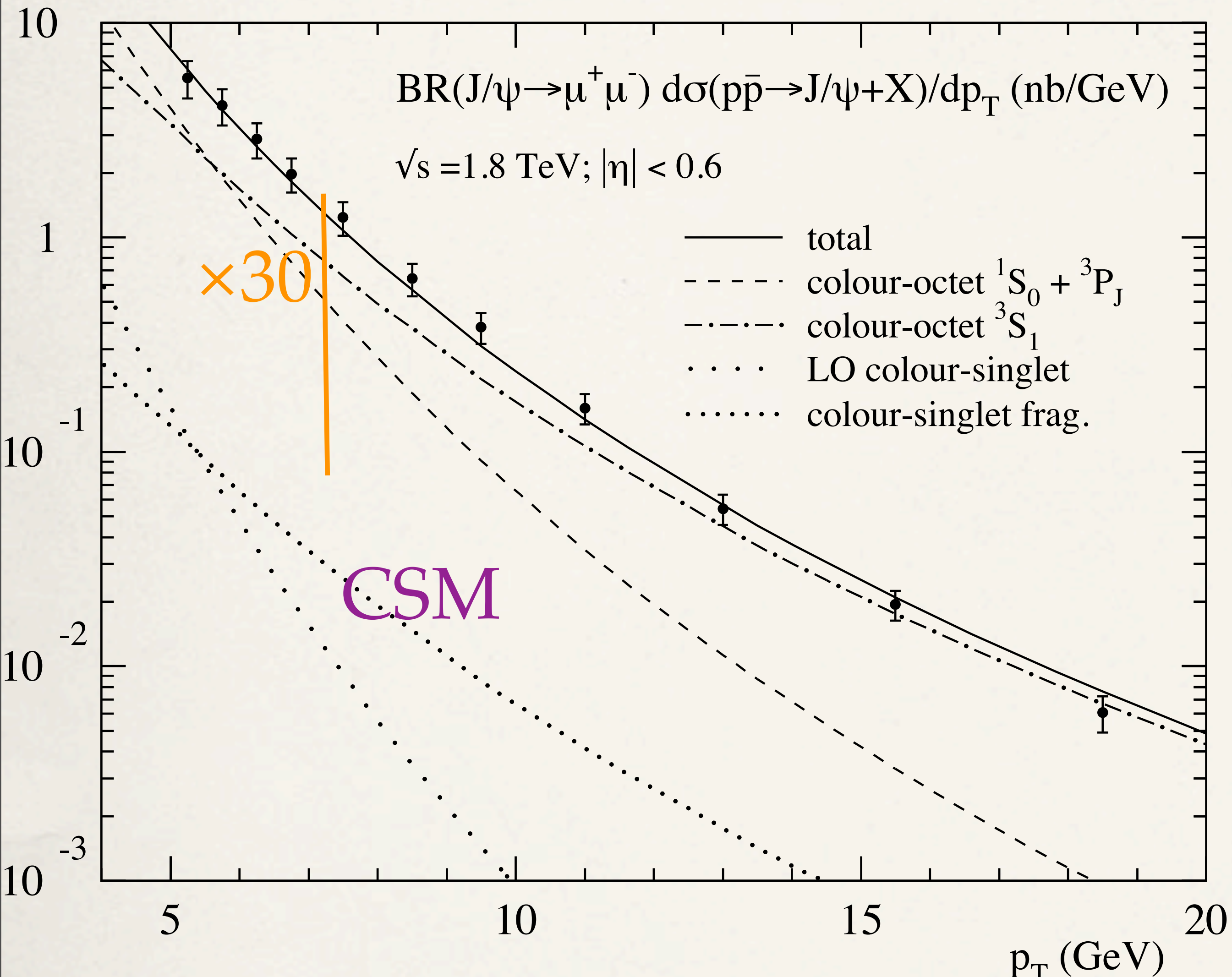
NRQCD factorization can accomodate the Tevatron data

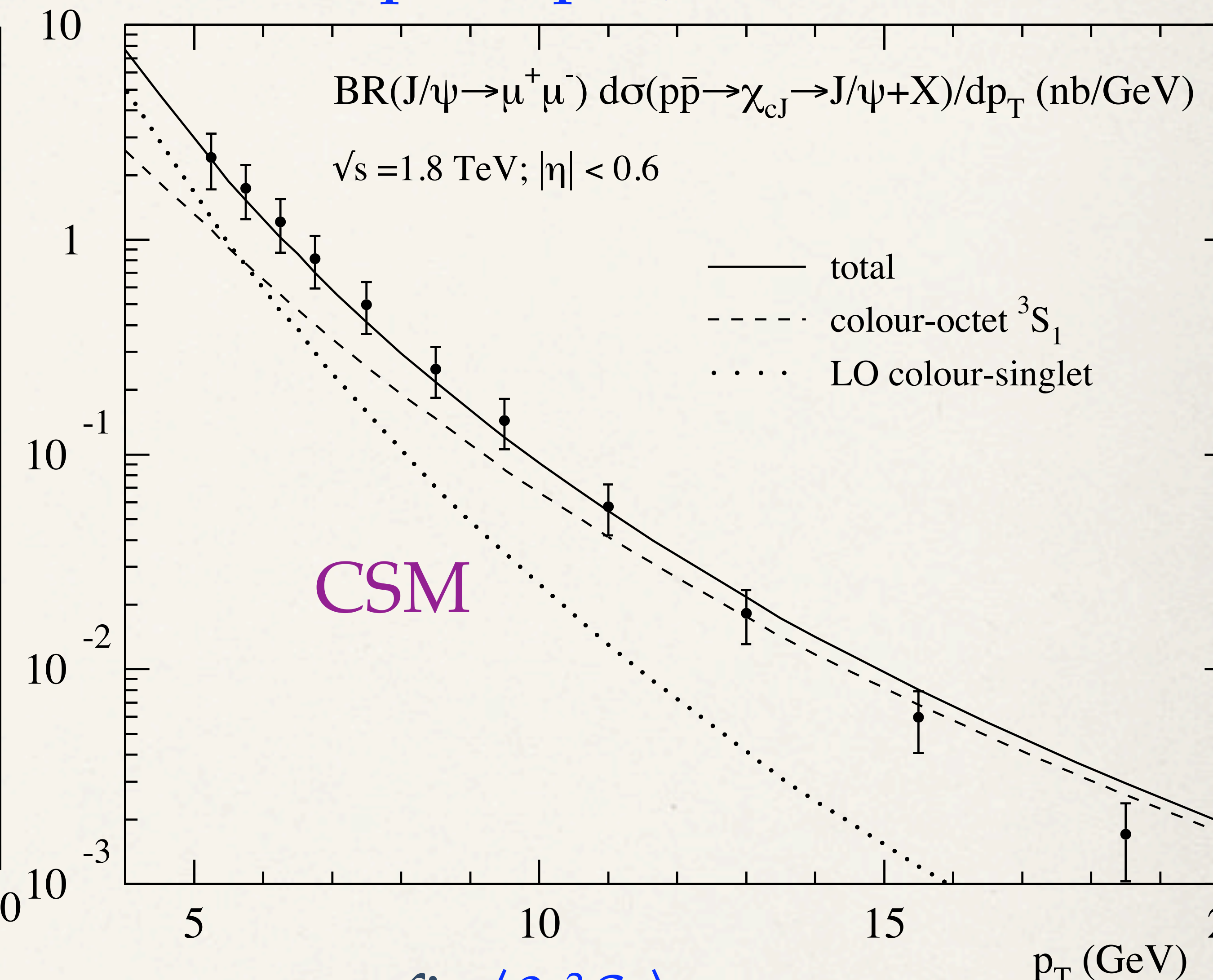
natural explanation with sound theoretical basis

NRQCD Factorization Model

CDF data

direct J/ψ | prompt χ_c





fit $\langle \underline{8}\ {}^3S_1 \rangle$ and $\langle \underline{8}\ {}^1S_0 \rangle$ | fit $\langle \underline{8}\ {}^3S_1 \rangle$

. Kramer 2001

NRQCD factorization can accomodate the Tevatron data

natural explanation with sound theoretical basis

NRQCD Factorization:
theory of quarkonium production?

- proof of NRQCD factorization formula?

$$d\sigma[H] = \sum_n d\hat{\sigma}[c\bar{c}(n)]\ \langle \mathcal{O}_n^H \rangle$$

- NRQCD matrix elements

    are they universal?

    can they be calculated using lattice QCD?

    is truncation of NRQCD factorization model adequate

- parton cross sections

    can higher orders in α_s be calculated?

Proof of NRQCD Factorization?

- NRQCD factorization formulas are conjectured
  motivated by perturbative QCD factorization theorems
  must be proven to all orders in α_s

- exclusive production

  $e^+ e^- \rightarrow$ quarkonium + quarkonium

  B $\rightarrow$ (light meson) + quarkonium

  proof of factorization to all orders in α_s

  Bodwin, Lee, Tormo 2008, 2010

- inclusive production in hadron collisions

  hadron + hadron $\rightarrow$ quarkonium + X

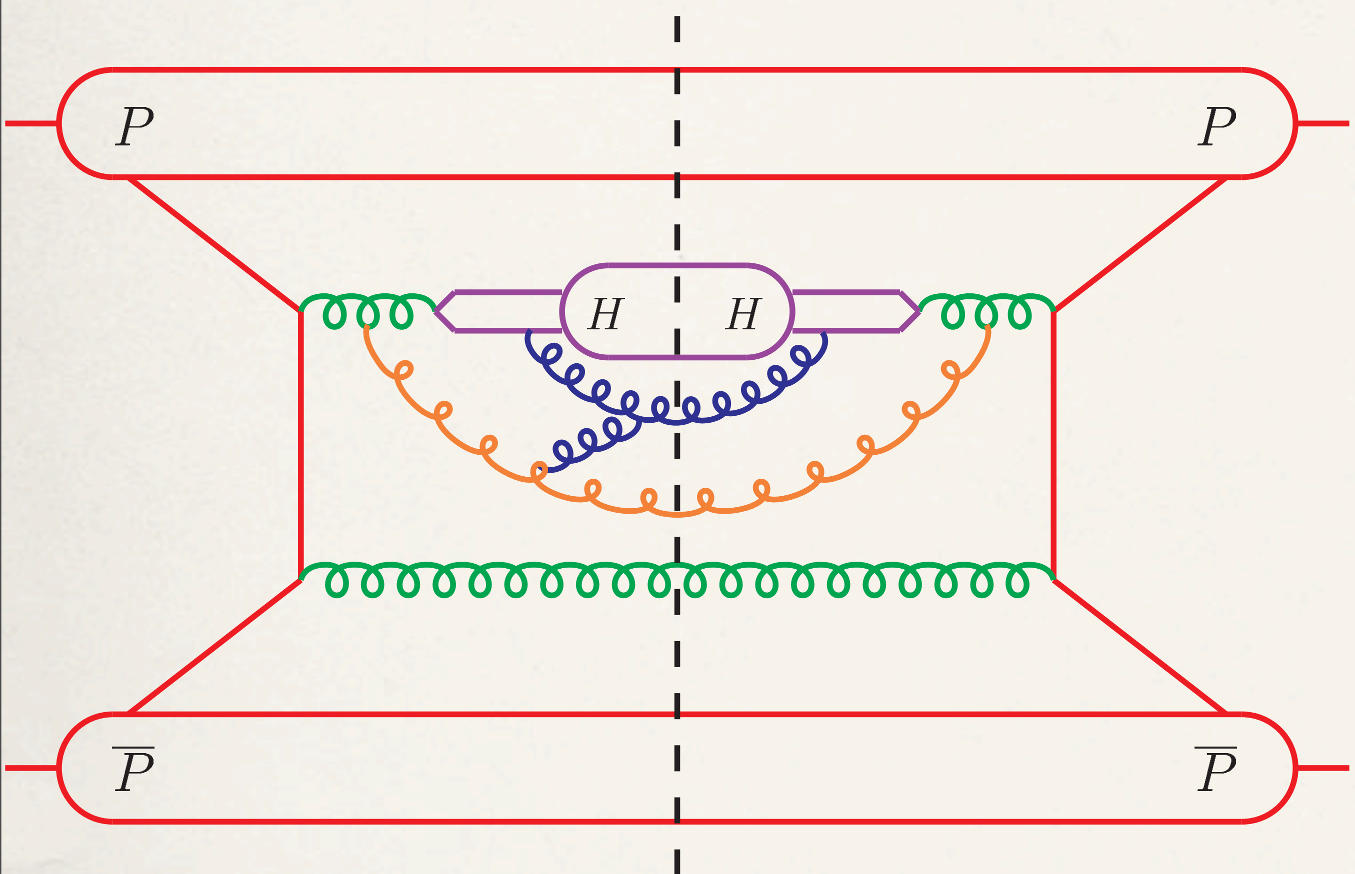
  verification of factorization to N^{2}LO in α_s

  eikonal line required in color-octet matrix elements

  Nayak, Qiu, Sterman 2005, 2006

Proof of NRQCD Factorization? (cont.)

- Nayak, Qiu, Sterman (2005, 2006): A key difficulty in proving factorization to all orders is the treatment of gluons with momenta of order m_c in the quarkonium rest frame.



- If the orange gluon has momentum of order m_c, it can't be absorbed into the NRQCD matrix element as a quarkonium constituent.
- But the orange gluon can have non-vanishing soft exchanges with the quarkonium constituents.
- The orange gluon can be treated as the eikonal-line part of the NRQCD matrix element, provided that the answer does not depend on the direction of the eikonal line (universality of the matrix elements).

- Nayak, Qiu, Sterman (2005, 2006): At two-loop order, the eikonal lines contribute but a "miracle" occurs: The dependence on the direction of the eikonal line cancels.

- In general, factorization of the inclusive cross section beyond two-loop order is still an open question.

- An all-orders proof is essential because the α_s associated with soft gluons is not small.

Proof of NRQCD Factorization? (cont.)

dramatic new development at this workshop!

proof of factorization to all orders in α_s at large p_T!

Jian-Wei Qiu and collaborators

- separate very hard scale p_T from not-so-hard scale m_Q
  by expanding in powers of m_Q^2/p_T^2

- at leading power: factorization (parton fragmentation)
  at order m_Q^2/p_T^2: factorization (QQ fragmentation)
  at higher orders: no factorization?

- not-so-hard factor involves scale m_Q
  and softer scales $m_Q v$ and smaller
  use NRQCD factorization to express it
  in terms of NRQCD matrix elements?

NRQCD matrix elements

$$d\sigma[H] = \sum_n d\hat{\sigma}[c\bar{c}(n)] \boxed{\langle \mathcal{O}_n^H \rangle}$$

- are they universal?

  in absence of proof, use phenomenology

- can they be calculated using lattice QCD?

  CSM matrix elements: YES, up to $O(v^4)$

  color-octet matrix elements: NO

- truncation of NRQCD factorization model

  S-waves: $\langle \underline{1}\ {}^3S_1 \rangle$, $\langle \underline{8}\ {}^3S_1 \rangle$, $\langle \underline{8}\ {}^1S_0 \rangle$, $\langle \underline{8}\ {}^3P_J \rangle$

  P-waves: $\langle \underline{1}\ {}^3P_J \rangle$, $\langle \underline{8}\ {}^3S_1 \rangle$

  is this sufficiently accurate for charmonium? maybe

  for bottomonium? maybe

Parton cross sections

$$d\sigma[H] = \sum_n \boxed{d\hat{\sigma}[c\bar{c}(n)]} \langle \mathcal{O}_n^H \rangle$$

accurate predictions require at least NLO in α_s

for charmonium, $\alpha_s(m_c) \approx 0.25$

for bottomonium, $\alpha_s(m_b) \approx 0.18$

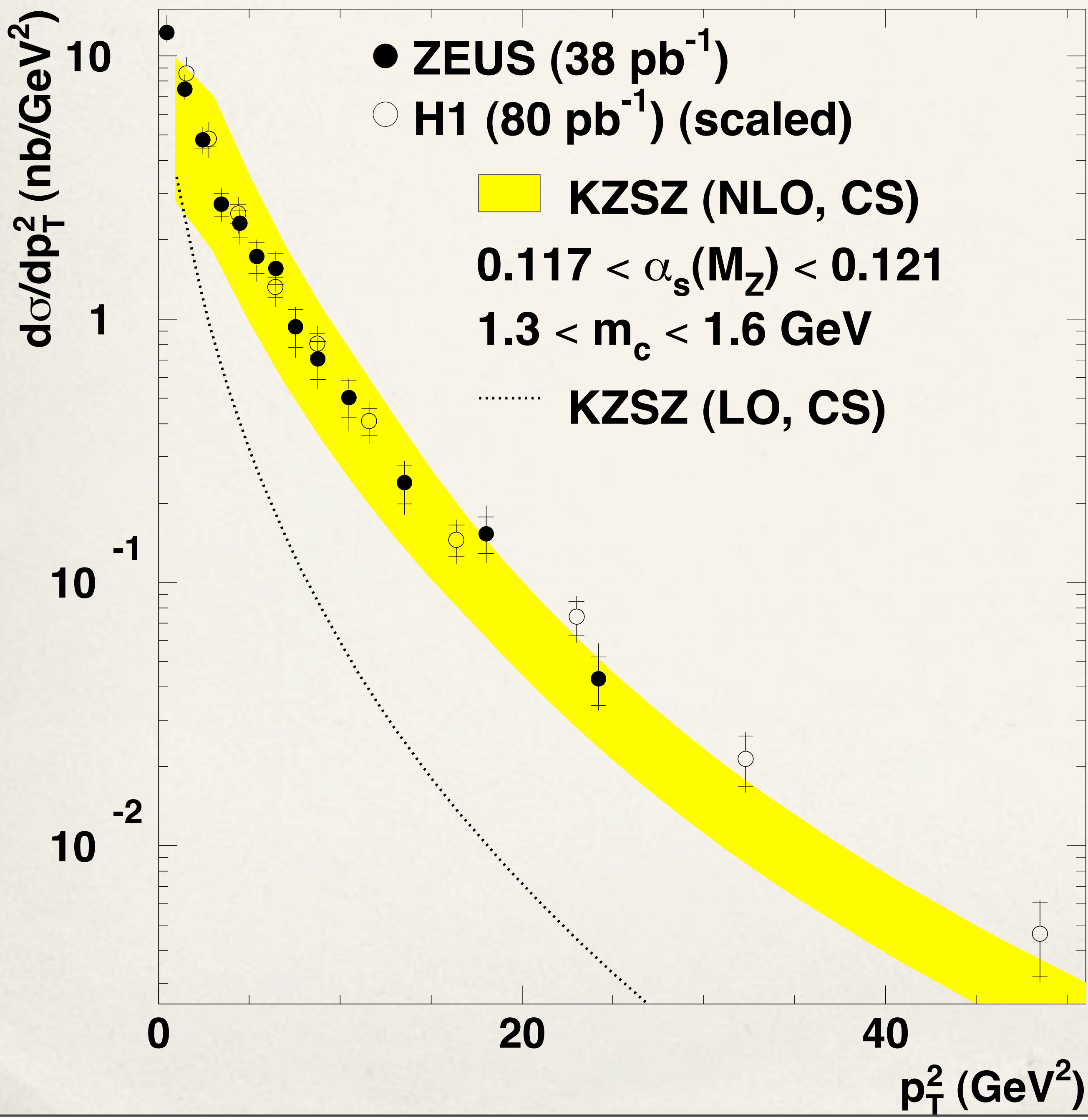
- photoproduction
  Kramer, Zunft, Steegborn, Zerwas 1995; Kramer 1996
  Artoisenet, Campbell, Maltoni, Tramontano 2009
  Chang, Li, Wang 2009; Li, Chao 2009
  Butenschoen, Kniehl 2009
- $\gamma\gamma$ collisions Klasen, Kniehl, Mihaila, Steinhauser 2005
- $e^+ e^- \rightarrow$ double charmonium
  Zhang, Gao, Chao 2005; Zhang, Ma, Chao 2008
  Gong, Wang 2008
- $e^+ e^- \rightarrow$ charmonium + X
  Zhang, Chao 2006; Ma, Zhang, Chao 2008
  Gong, Wang 2008, 2009
  Zhang, Ma, Wang, Chao 2009
- hadron collisions
  Petrelli, Cacciari, Greco, Maltoni, Mangano 1988
  Campbell, Maltoni, Tramontano 2008; Artoisenet, Lansberg, Maltoni, 2008
  Li, Wang 2008; Gong, Wang 2008; Gong, Li, Wang 2009

Phenomenological Status of NRQCD Factorization

- photoproduction
- $e^+ e^- \rightarrow$ double charmonium
- $e^+ e^- \rightarrow$ charmonium + X
- $\gamma\gamma$ collisions
- hadron collisions

Inelastic J/ψ Photoproduction Cross Section at HERA

- It had been believed that NLO color-singlet calculations leave little room for a color-octet contribution.

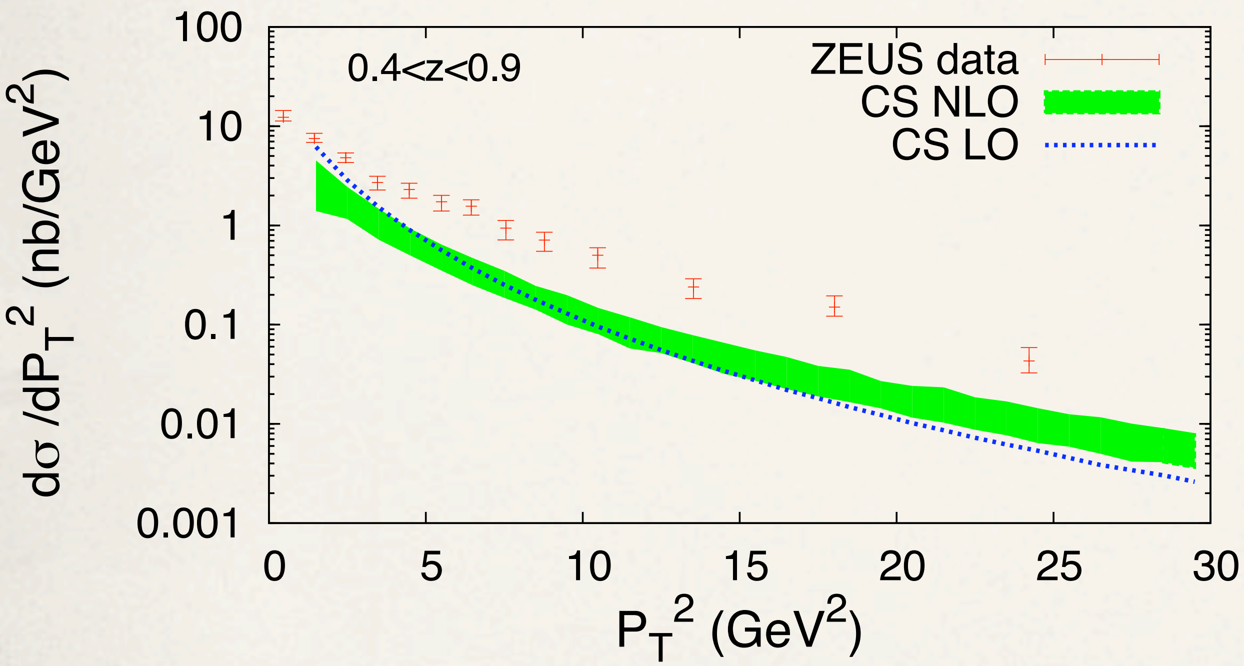


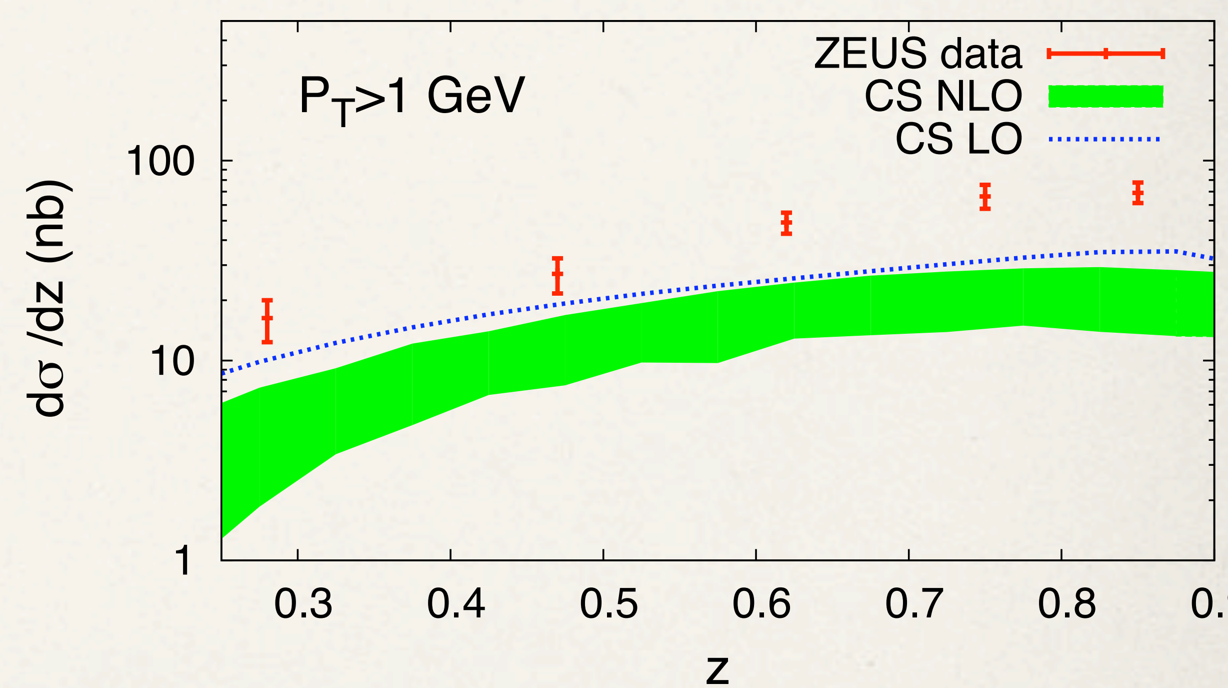
- NLO corrections increase the color-singlet contribution substantially. (Krämer, Zunft, Steegborn, Zerwas (1994); Krämer (1995))
- NLO corrections include $\gamma + g \rightarrow (c\bar{c}) + gg$, which is dominated by t-channel gluon exchange.
- For large p_T, this process goes as $\alpha_s^3 m_c^2/p_T^6$, instead of $\alpha_s^2 m_c^4/p_T^8$.

Photoproduction (cont.)

Recent Theoretical Developments

- Artoisenet, Campbell, Maltoni, Tramontano (2009): A new calculation of NLO color-singlet contribution
  - Confirms the analytic results of previous calculations.
  - But a more reasonable choice of renormalization/factorization scale ($\sqrt{4m_c^2 + p_T^2}$ instead of $m_c/\sqrt{2}$) yields much smaller numerical results for cross sections.





- Leaves room for a color-octet contribution.
- There is no longer an obvious conflict between the NRQCD prediction and the HERA data.

Double charmonium from e^+e^-

Exclusive Double-Charmonium Production at Belle and BABAR

$$e^+e^- \to J/\psi + \eta_c$$

- Experiment
  Belle (2004): $\sigma[e^+e^- \to J/\psi + \eta_c] \times B_{>2} = 25.6 \pm 2.8 \pm 3.4$ fb.
  BABAR (2005): $\sigma[e^+e^- \to J/\psi + \eta_c] \times B_{>2} = 17.6 \pm 2.8^{+1.5}_{-2.1}$ fb.

larger by ≈5

- NRQCD at LO in α_s and v
  Braaten, Lee (2003): $\sigma[e^+e^- \to J/\psi + \eta_c] = 3.78 \pm 1.26$ fb.
  Liu, He, Chao (2003): $\sigma[e^+e^- \to J/\psi + \eta_c] = 5.5$ fb.
  The two calculations employ different choices of m_c, NRQCD matrix elements, and α_s.
  Braaten and Lee include QED effects.
  Confirmed by Brodsky, Ji, and Lee in light-front QCD in the quarkonium nonrelativistic limit.

- Exclusive process: the color-octet contribution is suppressed as v^4.

- The LO color-singlet matrix elements are determined from $\eta_c \to \gamma\gamma$ and $J/\psi \to e^+e^-$.

Double charmonium from e^+e^-

α_s Corrections to $e^+e^- \to J/\psi + \eta_c$

- An important step in resolving the discrepancy:
  Zhang, Gao, Chao (2005) found that corrections at NLO in α_s yield a K factor of about 1.96.
- Confirmed by Gong and Wang (2007).
- Not enough to bring theory into agreement with experiment.

relativistic corrections: $\times 1.5$?

- Theory and experiment agree within uncertainties:
  - Theory: $\sigma[e^+e^- \to J/\psi + \eta_c] = 17.6^{+8.1}_{-6.7}$ fb
  - Belle: $\sigma[e^+e^- \to J/\psi + \eta_c] \times B_{>2} = 25.6 \pm 2.8 \pm 3.4$ fb.
  - BABAR: $\sigma[e^+e^- \to J/\psi + \eta_c] \times B_{>2} = 17.6 \pm 2.8^{+1.5}_{-2.1}$ fb.
- *Caveat:* $B_{>2}$ is not known.
  - Could be as small as 0.5–0.6.
  - Even so, the error bars of theory and the BABAR experiment overlap.
- Zhang, Ma, Chao (2008): In the cases of $\sigma[e^+e^- \to J/\psi(\psi(2S)) + \chi_{c0}]$, large K factors (~ 2.8) may bring theory into agreement with experiment.

Inclusive Double $c\bar{c}$ Production at Belle

- Belle (2002):

$$\frac{\sigma[e^+e^- \to J/\psi + c\bar{c} + X]}{\sigma[e^+e^- \to J/\psi + X]} = 0.59^{+0.15}_{-0.13} \pm 0.12$$

- pQCD plus color-singlet model (Cho, Leibovich (1996); Baek, Ko, Lee, Song (1997); Yuan, Qiao, Chao (1997)):

$$\frac{\sigma[e^+e^- \to J/\psi + c\bar{c} + X]}{\sigma[e^+e^- \to J/\psi + X]} \approx 0.1$$

- There is a significant disagreement between experiment and the LO color-singlet model.

Inclusive J/ψ + charm from e^+e^- (cont.)

NLO corrections: Zhang , Chao 2007; Gong, Wang 2009
Ma, Zhang, and Chao 2008; Gong, Wang 2009

Effect of NLO calculations on the ratio

- NLO calculations significantly reduce the discrepancy between theory and experiment for the ratio of cross sections:

$$\frac{\sigma[e^+e^- \to J/\psi + c\bar{c} + X]}{\sigma[e^+e^- \to J/\psi + X]} \approx 0.5$$

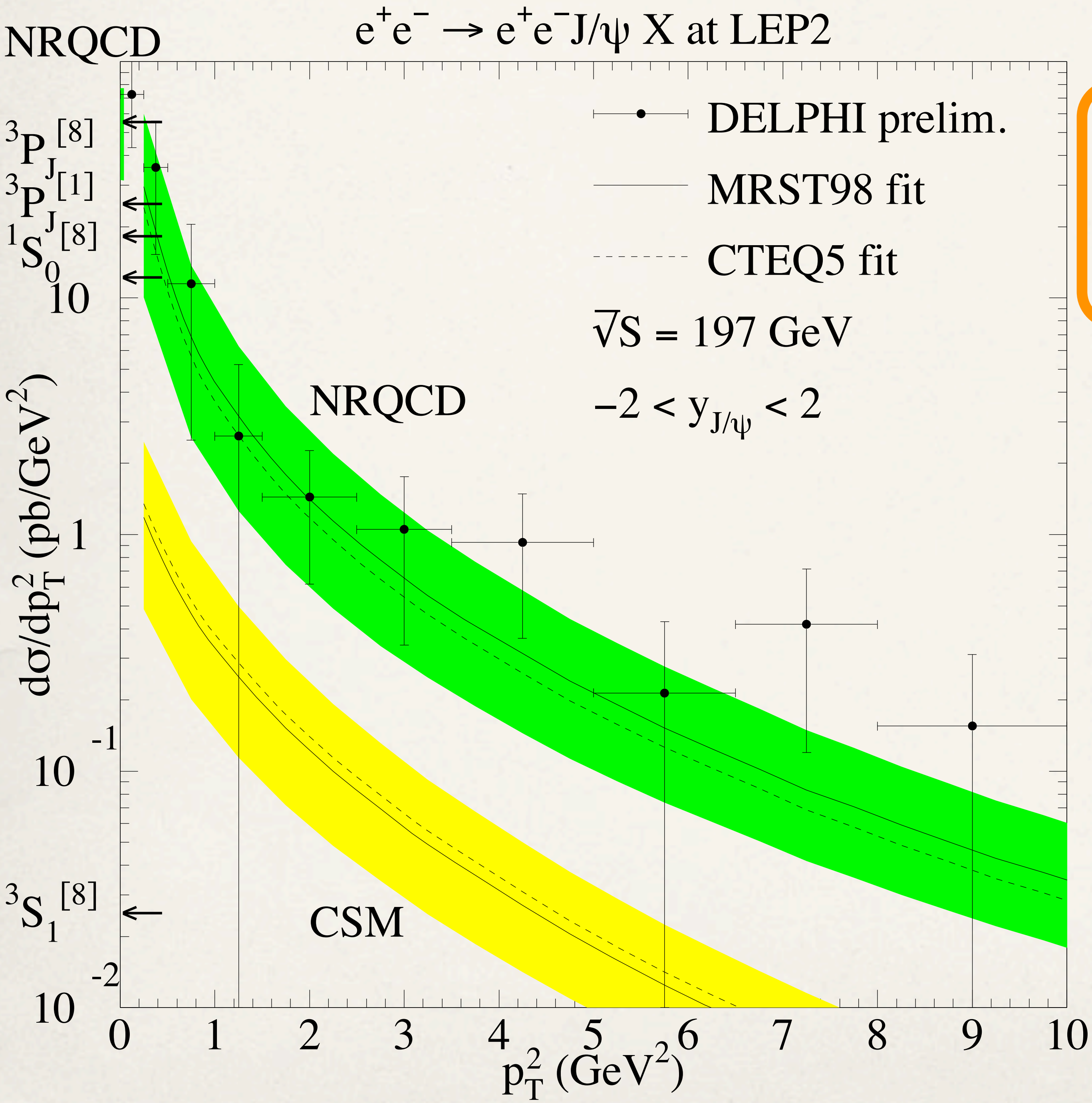
  – Only color-singlet contributions are included.

- No longer an apparent disagreement between experiment and color-singlet theory.
- It would be good to have a detailed error analysis for the theoretical prediction.
- It is important for BABAR to check the Belle results for inclusive double-$c\bar{c}$ production.

Belle: $$\frac{\sigma[e^+e^- \to J/\psi + c\bar{c} + X]}{\sigma[e^+e^- \to J/\psi + X]} = 0.59^{+0.15}_{-0.13} \pm 0.12$$

Inclusive J/ψ from $\gamma\gamma$

$$\gamma\gamma \to J/\psi + X \text{ at LEP}$$



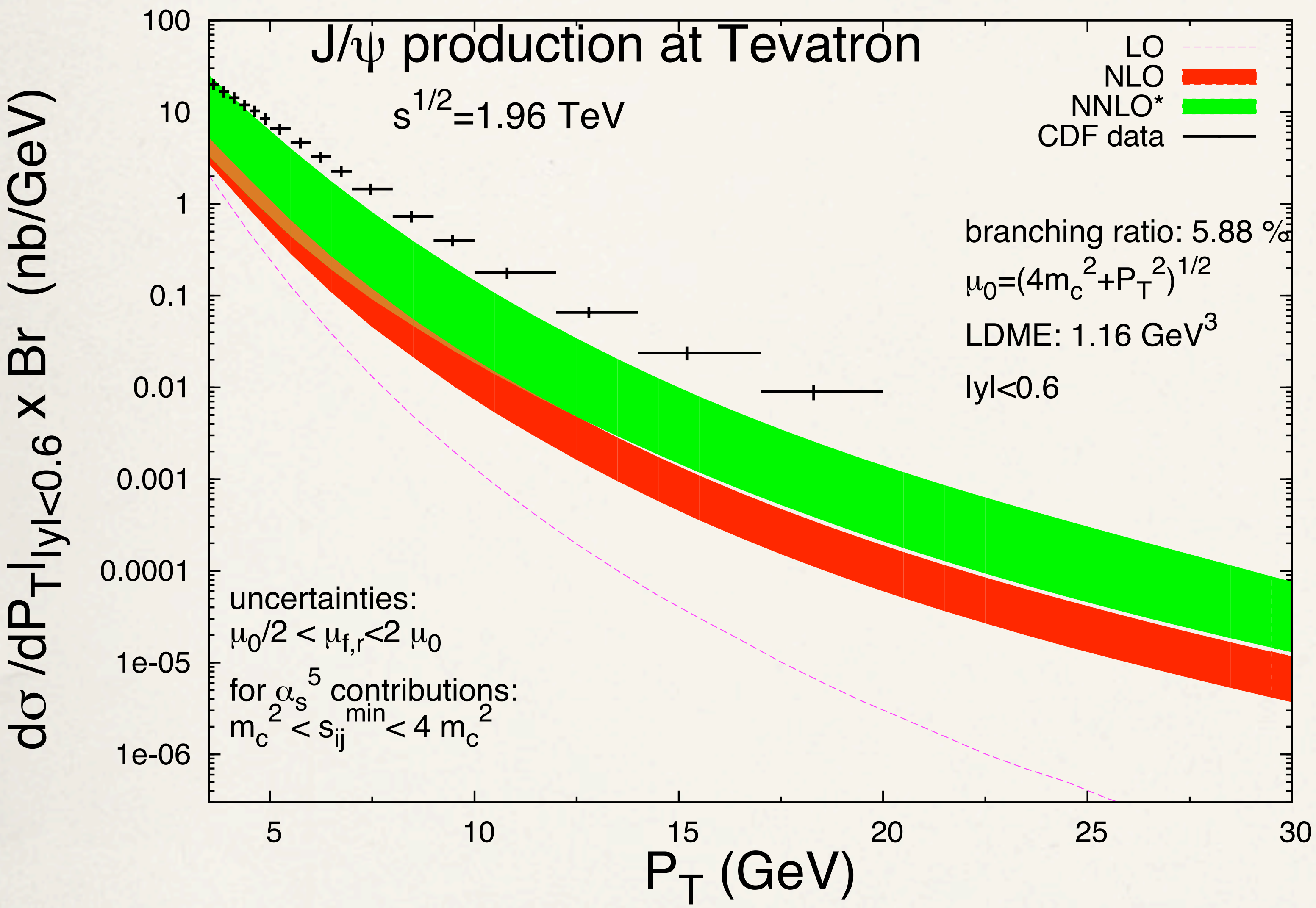
- Comparison of theory (Klasen, Kniehl, Mihaila, Steinhauser) with Delphi data clearly favors NRQCD over the color-singlet model.
- Theory uses Braaten-Kniehl-Lee matrix elements from Tevatron data and MRST98LO (solid) and CTEQ5L (dashed) PDF's.
- Theoretical uncertainties from
  - Renormalization and factorization scales (varied by a factor 2),
  - NRQCD color-octet matrix elements,
  - Different linear combination of matrix elements than in Tevatron cross sections.

J/ψ Production in DIS at HERA

- Note that NLO calculations are not yet available for this process.
- The NRQCD (Kniehl, Zwirner (2001)) prediction uses Braaten-Kniehl-Lee (1999) matrix elements extracted from the Tevatron data and MRST98LO and CTEQ5L PDF's.
- Theoretical uncertainties from
  - PDF's,
  - Renormalization and factorization scales (varied by a factor 2),
  - NRQCD color-octet matrix elements,
  - Different linear combination of matrix elements than in Tevatron cross sections.

New Results for J/ψ Production

- Color-singlet contribution:

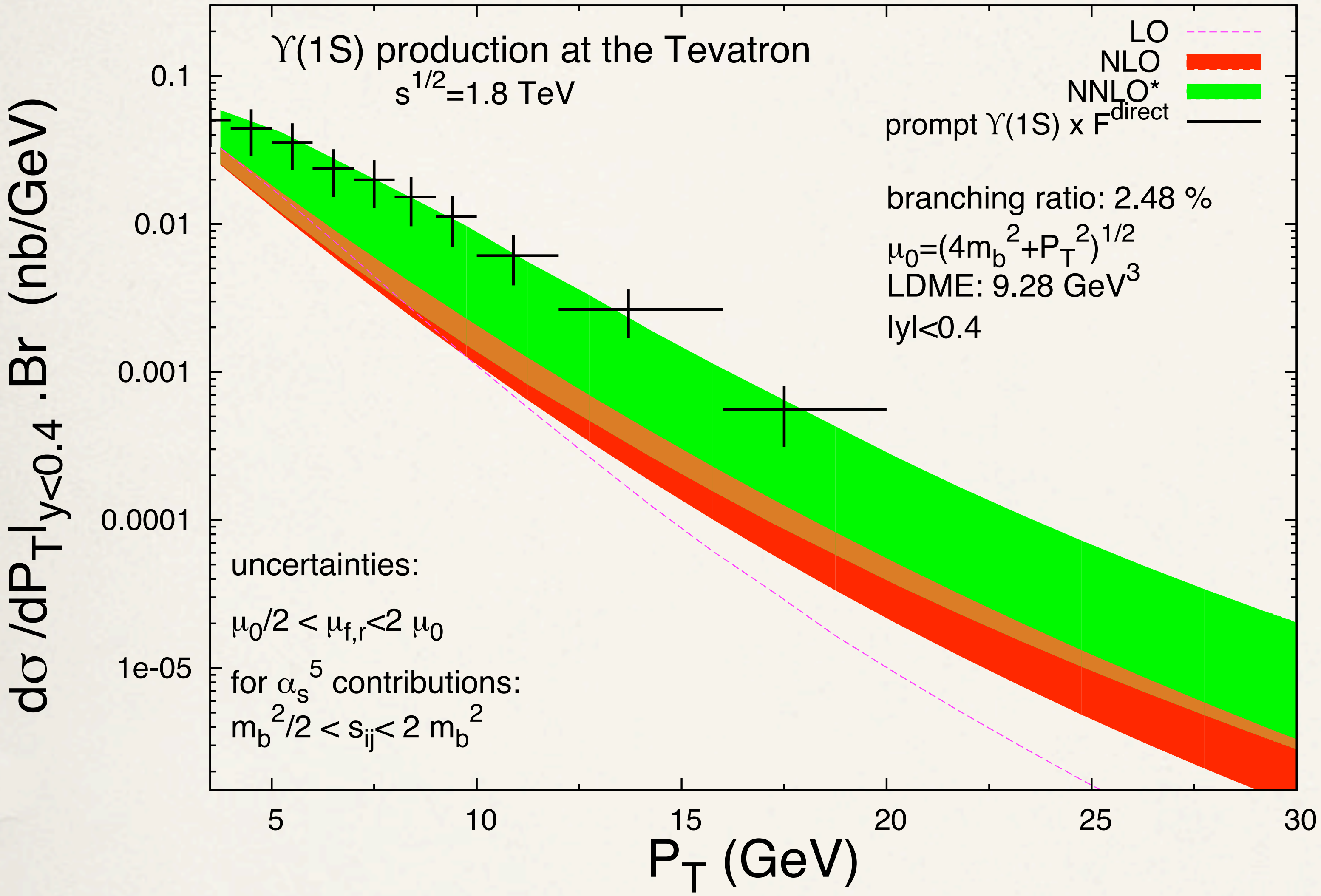


- Plot from Pierre Artoisenet, based on work by Artoisenet, Campbell, Lansberg, Maltoni, Tramontano (in progress)
- The NNLO* calculation is an estimate based on real-emission contributions only.
- The data still seem to require a color-octet contribution, but its size may be reduced from previous estimates. Affects the matrix elements used to compute all other processes.

- Color-octet contribution:
  NLO corrections are about 14% (Gong, Li, and Wang (2008)).

Inclusive quarkonium at Tevatron

New Results for Color-Singlet Υ Production

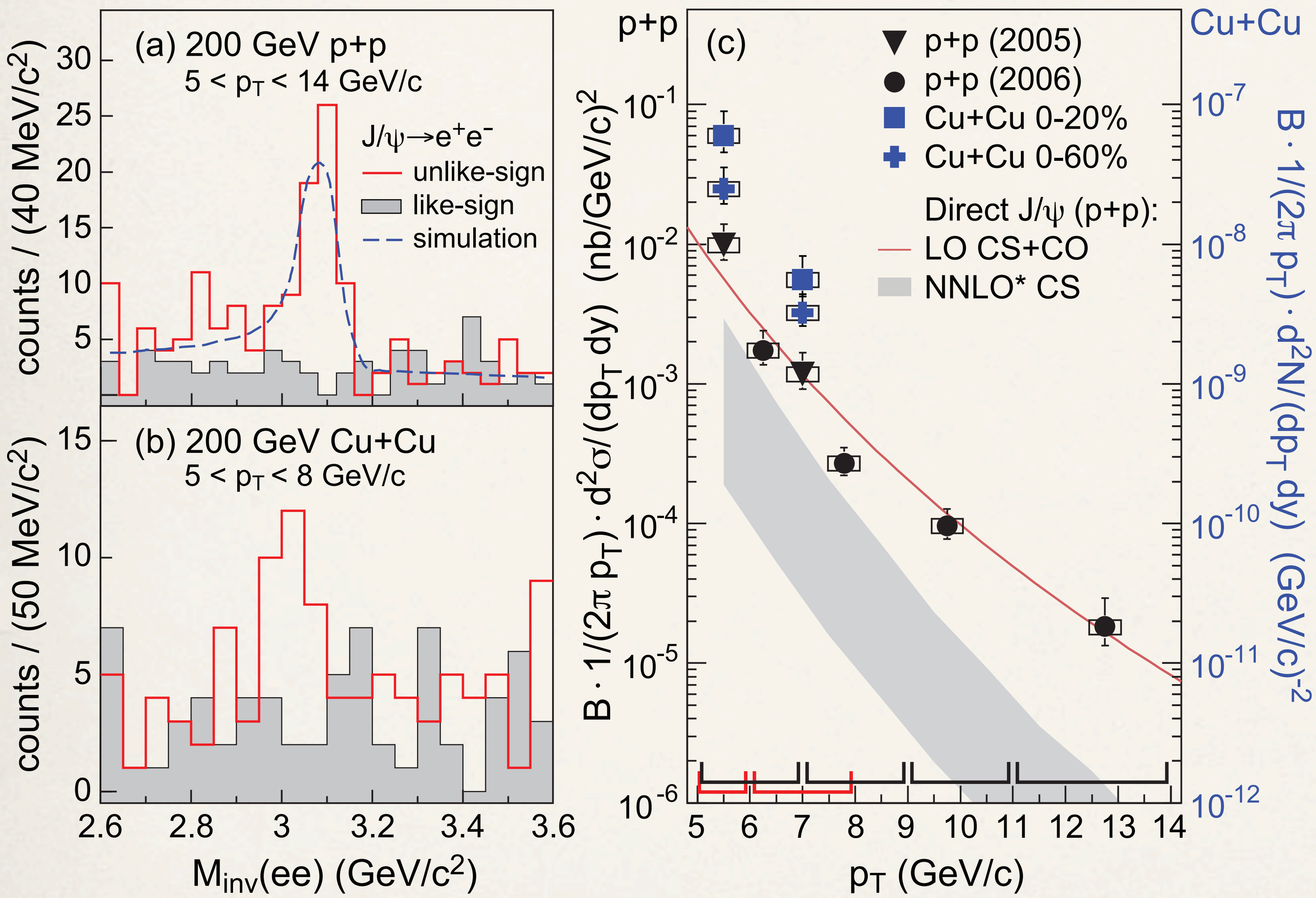


- Plot from Pierre Artoisenet, based on work by Artoisenet, Campbell, Lansberg, Maltoni, Tramontano (2008)
- NLO results confirmed by Gong and Wang (2007).

- The data could be explained by color-singlet production alone.
- There is still room for a substantial amount of color-octet production.
- Color-octet production is suppressed as v^4.
  Should be smaller for Υ ($v^2 \approx 0.1$) than for J/ψ ($v^2 \approx 0.3$).

J/ψ Production at RHIC

- The STAR Collaboration has measured the J/ψ p_T distributions in $p+p$ and Cu+Cu collisions:



- The LO color-singlet plus color-octet calculation (Nayak, Liu, Cooper (2003)) fits the data well.
  - Does not include feeddown from $\psi(2S)$, χ_c, or B decays. (Estimated to be a factor 1.5.)

Polarization

NRQCD factorization

predicts the polarization of quarkonium
with no additional parameters

dramatic qualitative prediction for hadron collisions:

direct J/ψ, Υ transversely polarised at large p_T

Cho, Wise 1995

- at sufficiently large p_T, charmonium production
  is dominated by gluon fragmentation

$$g + g \to g^* + g$$

- at LO in α_s, gluon fragments into color-octet $c\bar{c}$ pair
  that inherits transverse polarization of gluon

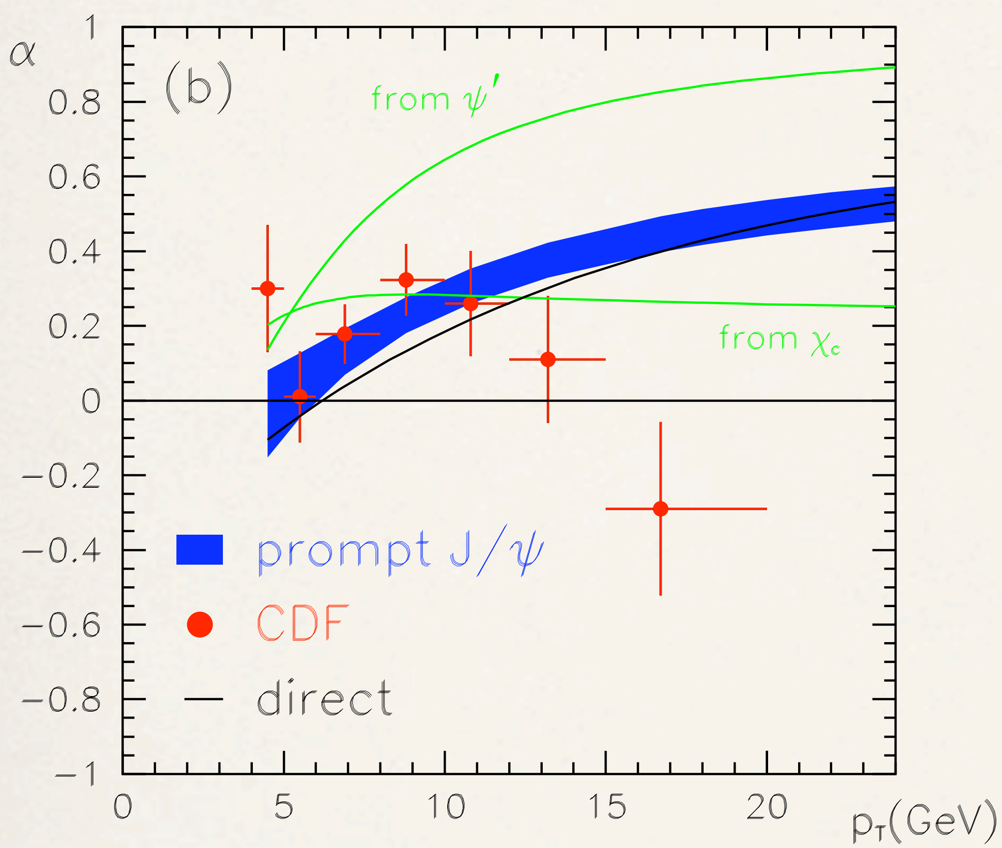
$$g^* \Uparrow \ \to \ c\bar{c}(\underline{8}\ {}^3S_1) \Uparrow$$

- at LO in v, hadronization into ${}^3S_1$ charmonium
  preserves transverse polarization of $c\bar{c}$ pair

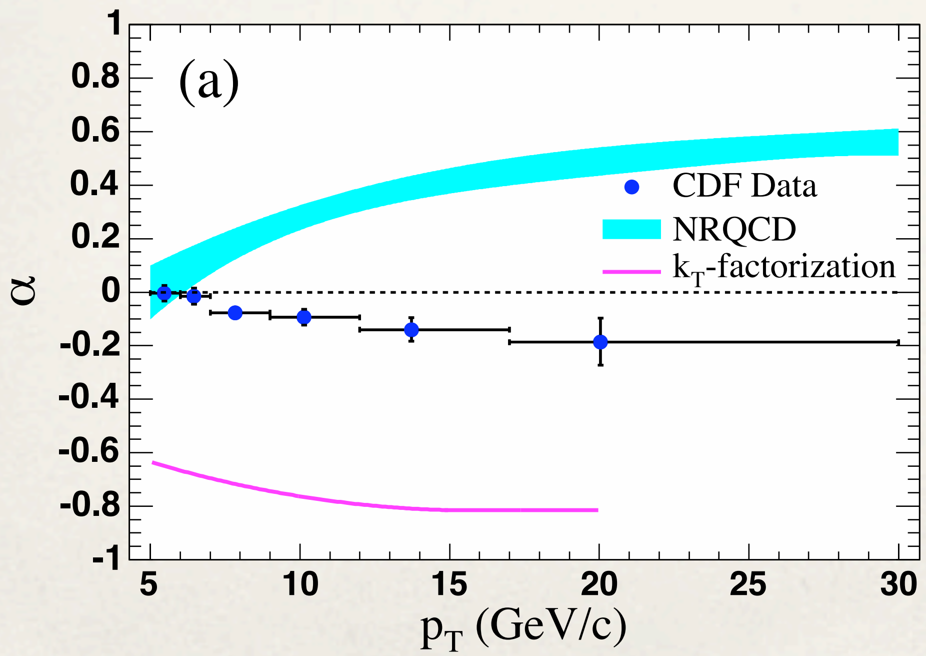
$$c\bar{c}(\underline{8}\ {}^3S_1) \Uparrow \ \to \ J/\psi \Uparrow \ + \ X$$

J/ψ Polarization

Run I:



Run II:

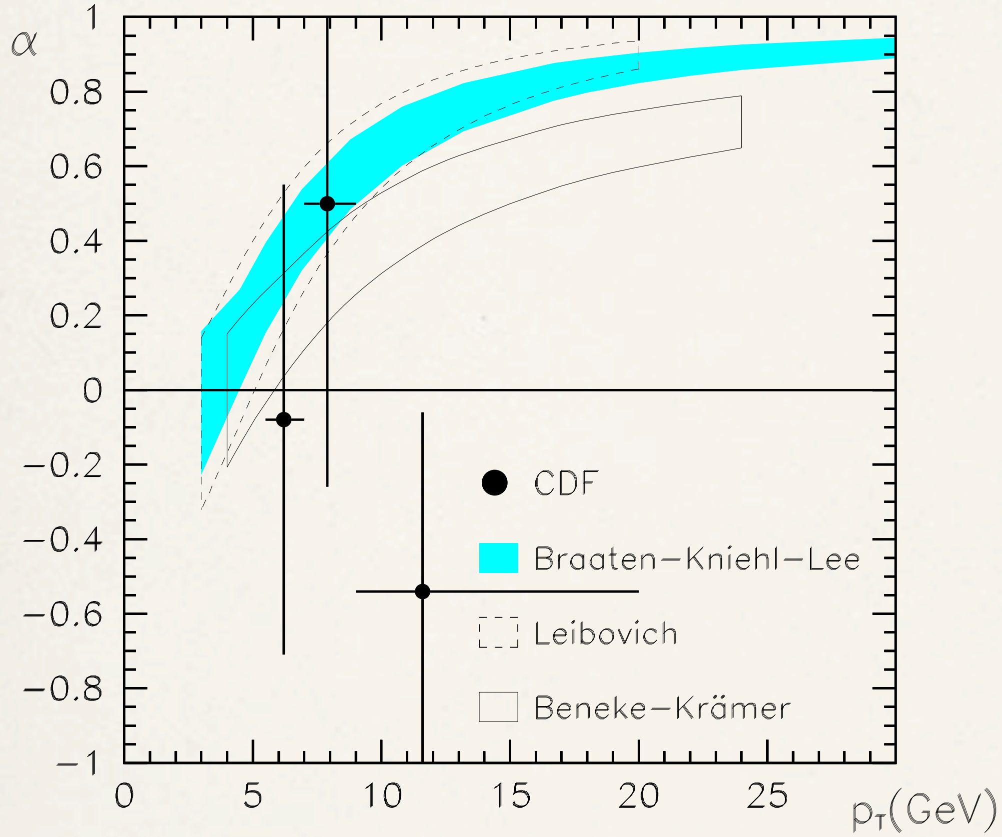


- $d\sigma/d(\cos\theta) \propto 1 + \alpha\cos^2\theta$.
  - $\alpha = 1$ is completely transverse;
  - $\alpha = -1$ is completely longitudinal.
- NRQCD prediction from Braaten, Kniehl, Lee (1999).
  - Feeddown from χ_c states is about 30% of the J/ψ sample and dilutes the polarization.
  - Feeddown from $\psi(2S)$ is about 10% of the J/ψ sample and is largely transversely polarized.
- Run I results are marginally compatible with the NRQCD prediction.
- Run II results are inconsistent with the NRQCD prediction.
- Also, inconsistent with Run I results.
  CDF was unable to track down the source of the Run I-Run II discrepancy.

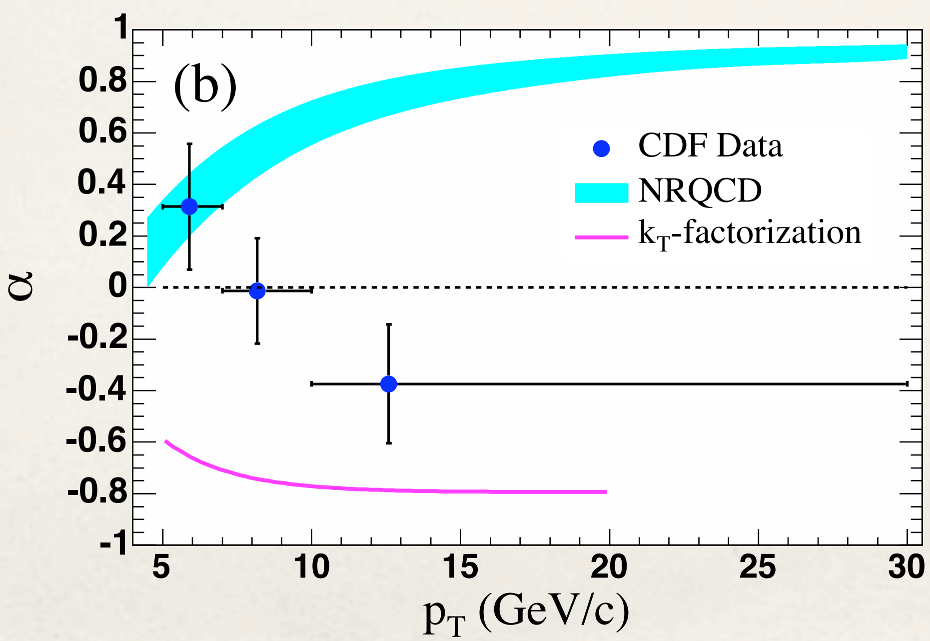
Polarization (cont.)

$\psi(2S)$ Polarization

Run: I



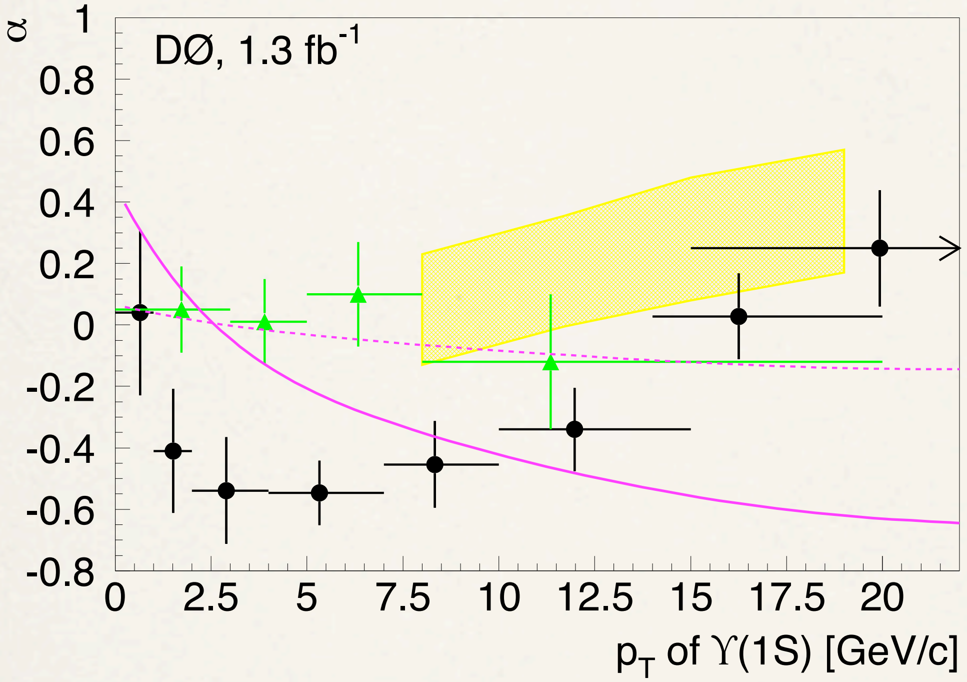
Run: II



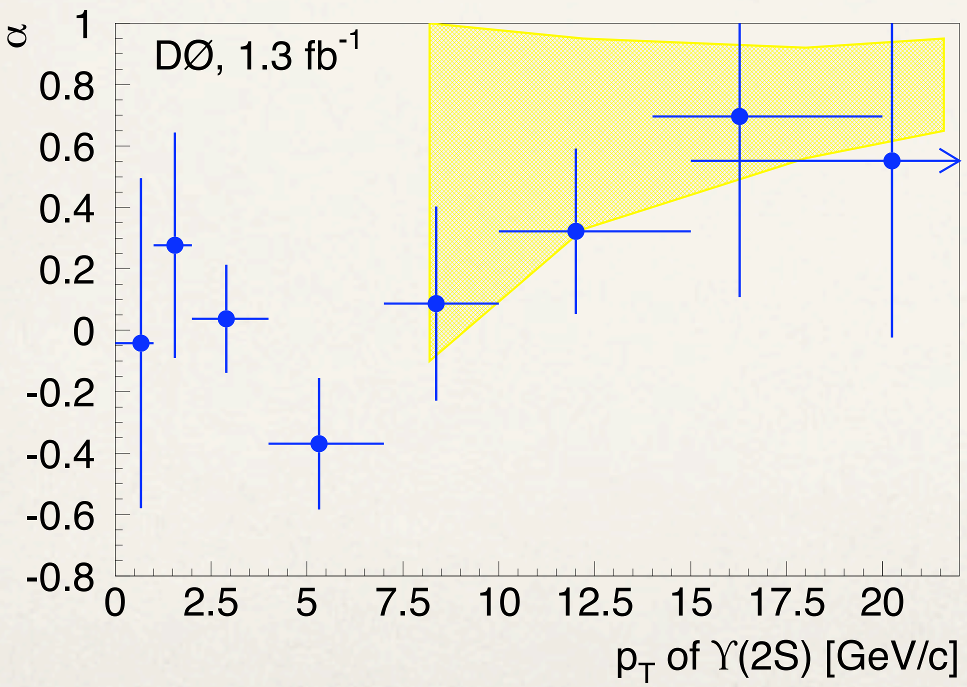
- The Run II data are incompatible with the NRQCD prediction.

Υ Polarization

$\Upsilon(1S)$ Polarization:



$\Upsilon(2S)$ Polarization:



- In the $\Upsilon(1S)$ case, the D0 results (black) are incompatible with the CDF results (green).
- The CDF results are compatible with the NRQCD prediction (yellow).
- The D0 results are marginally incompatible with the NRQCD prediction.
- The curves are the limiting cases of the k_T-factorization prediction.
- In the $\Upsilon(2S)$ case, the theoretical and experimental error bars are too large to make a stringent test.

Polarization (cont.)

Are still higher order perturbative QCD calculations
necessary for polarization?
Does NRQCD factorization fail for polarization?

new development at this workshop!
large-p_T factorization Jian-Wei Qiu et al.

- expand in powers of m_Q^2 / p_T^2
  to separate scales m_Q and p_T

- at leading power: parton fragmentation $\Rightarrow$ T
  at order m_Q^2 / p_T^2: $Q\bar{Q}$ fragmentation $\Rightarrow$ L

- Will predictions including $Q\bar{Q}$ fragmentation
  agree with data?

Stumbling towards a Theory of Quarkonium Production

Color-singlet model (1976-1995)
Color evaporation model (1977-?)

NRQCD factorization

- still a viable theory of quarkonium production!
- exclusive quarkonium: proven to all orders
- inclusive quarkonium: verified to NNLO
- can it be combined with large-p_T factorization?

NRQCD factorization model

S-wave multiplets: 3 color-octet parameters
P-wave multiplets: 1 color-octet parameter

- still a viable model of charmonium production
  bottomonium production

Stumbling towards a Theory of Quarkonium Production

NLO perturbative QCD corrections

- have removed most dramatic discrepancies
  between NRQCD factorization and experiment
  (polarization is important exception)
- decrease the importance of color-octet contributions

Large-p_T factorization

Jian-Wei Qiu et al.

- separates scales m_Q and p_T
- introduces QQ fragmentation
- still requires NRQCD factorization
  to reduce production rates to a few constants

Experimental outlook

- final results from B factories (Belle, Babar)
  DESY (H1, Zeus)
  Tevatron (CDF, D0)

- first results from LHC experiments
  extend charmonium out to fragmentation region
  high statistics measurements of bottomonium
  additional results from RHIC

- future results from super-B factories

Will NRQCD factorization
remain a viable theory of quarkonium production?